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A temporal interpolation method to obtain hourly atmospheric surface pressure tides in Reanalysis 1979-1995

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Abstract. The diurnal cycle in climatology as revealed in National Centers for Environmental Prediction's Reanalysis 1979-1995 has been studied for global gridded data at 0000, 0600, 1200 and 1800 UT. Climatologies have been prepared for each of the four time levels separately. There are substantial differences in, for instance, the 0000 and 0600 UT climatologies, owing to a diurnal cycle and/or what is referred to commonly as atmospheric tides. The semidiurnal tide is quite strong in the mass fields, but with sampling every 6 hours at the Nyquist frequency, some aspects cannot be studied properly. However, a method of interpolation based on spatial harmonic waves moving at an empirically determined speed can be called upon to make an educated guess about the atmospheric tides at any times in between. This interpolation technique is similar to the one published by *Van den Dool and Qin* [1996], but the wave speeds are not like the slow Rossby modes but roughly 15° westward per hour. We present the global tides in surface pressure thus obtained for every hour of the day for January.

1. Introduction

When the word *climatology* is used, many researchers will associate this with something that is a virtual constant, and if the climate changes at all, the change is slow. There are, however, variations on the (sub)daily timescale which are regular enough to be called climatological; they are due to the repetitive and predictable daily variation in solar heating. Global analyses have rarely been made available more than once or twice a day, so this daily variation, which is entirely obvious from local hourly observations at any station anywhere around the world, has not been documented well to date in the context of global gridded analyses.

The Reanalysis project at the National Centers for Environmental Prediction (NCEP) [*Kalnay et al.,* 1996], which presently has data available for 1979-1995, has been conducted specifically for climatological applications, although the technologies used are not necessarily climatological but were developed in conjunction with decades of research in numerical weather prediction. The Reanalysis data set features global gridded analyses of the instantaneous state of many quantities at 28 levels in the atmosphere and the Earth's surface at 0000, 0600, 1200 and 1800 UT. This allows us to study differences in climatology at these four sampling times and get some impression of the daily climatological variation of many fields.

There are substantial differences in, say, the 0000 and 0600 UT climatologies of many fields, owing to a diurnal cycle, and/or what is referred to commonly, for lack of a better word, as atmospheric tides, solar tides that is. (Except for a comment in the discussion, the tides in this paper are always the solar heating induced tides, not gravitational tides which are very very small.) The semidiurnal tide in the mass fields has been known to be substantial for a long time [*Chapman,* 1951; *Chapman and Lindzen,* 1970; *Riehl,* 1954], and although most obvious in the tropics, it is a truly global phenomenon.

The few earlier attempts to document tidal fluctuations in gridded data include work by *Hsu and Hoskins* [1989], who used data for a few seasons in 1986 and 1987. *Caplan and White* [1989] and *White and Caplan* [1991] noted that the systematic error in the NCEP (then the National Meteorological Center (NMC)) forecasts contained a semidiurnal component. Prior to implementation of the work by *Ballish et al.,* [1992], the tides were nearly eliminated from the operational analysis at NCEP, thus creating a semidiurnal systematic difference between forecast and analysis. Curiously enough, the forecast was better than the analysis. The modern, long and homogeneous Reanalysis data set should be a great improvement over the data used in earlier studies.

While the semidiurnal cycle can be easily seen in data every 6 hours, certain formal calculations (for example, as to the temporal phase of the tide) are difficult

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with sampling at the Nyquist frequency. Ideally, we would need data more frequently for proper analysis. To this end, a method of interpolation based on spatial harmonic waves moving at an empirically determined speed will be used here to produce climatology fields at any in-between time. The interpolation technique used here is basically the same as the one published by *Van den Dool and Qin* [1996] (hereafter referred to as DQ), but the wave speeds are completely different. While in DQ *anomalies* were moving like slow Rossby modes, the tides are traveling at the much faster speed of roughly 90° of longitude westward per 6 hours. Moreover, in DQ the moving anomaly waves were calculated as instantaneous fields at 0000 UT minus a 0000 UT climatology, i.e., a more frequently used nomenclature for the notion *anomaly*. In the present work, however, it is the climatology itself that moves. We will now use the notion anomaly in this paper for the departure of the climatology at at a specific time from the daily mean climatology.

Apart from the unusual definition of anomaly (departure of climatology at xxxx UT from daily mean climatology, where xxxx=0000,0100,....., 2400), the nomenclature for daily cycle, etc., should be clarified. We will use the word cycle only when it refers specifically to a Fourier component in time, i.e., the daily (semidaily) cycle is the Fourier component with a 24 (12) hour period, also denoted as $s = 1, 2$, etc. On the other hand, daily variation is just the time trace of surface pressure over a 24 hour period. Fourier analysis in space will be referred to as yielding zonal harmonic waves $m = 1, 2$, etc.

The explicit purpose of the paper is to show how the proposed interpolation technique performs on atmospheric tides, and in the process we do document several aspects of the tides in Reanalysis. However, our interest in the subject of tides is related to the question of global mass redistribution [*Van den Dool and Saha,* 1993], and the divergent mass fluxes (and mass sources and sinks) that are associated with the climatological pressure variations that are observed. *Van den Dool and Saha* [1993] only dealt with the climatological annual surface pressure variation in a general circulation model. With the advent of analysis (Reanalysis rather), and more frequent data output (both models and analyses), we can now contemplate studying the daily and annual variation in surface pressure in a model and in the real world. For this purpose, one needs to know the time derivative of surface pressure with good accuracy. From 6 hourly data alone the time derivative associated with the tides can not be calculated with any fidelity. Nor can linear (or higher order) time interpolation (LTI) add much information.

We will present the global tides in surface pressure for every hour of the day for January. In the process we will comment on how reliable the tides are in the Reanalysis, as far as one can judge. Classical texts [*Chapman,* 1951; *Riehl,* 1954] have described the atmospheric tides as having an amplitude of 1-1.5 mbar, and maxima (minima) at 1000/2200 (1600/0400) local time. The tides in a 17 year model run will be mentioned to check whether the Reanalysis errors, if any, are due to the model used to produce a guess field in the data assimilation. Also, hourly data from a 2 month model run will be used to demonstrate that fields interpolated from 6 hourly data yield indeed an accurate depiction of hourly model output. Finally, we will comment on aspects of the tides in other calendar months, where needed.

2. Data and Definition of Climatology

The data used are from NCEP's Reanalysis [*Kalnay et al.*,1996]. Specifically, we use the surface pressure field from 1979 through 1995, sampled four times a day at full model resolution. The fields are on a 192x94 Gaussian grid used commonly in association with a T62 horizontal spectral resolution. In longitude the grid distance is a constant 1.875°. In latitude the grid distance is just below 2° as well, but not quite constant with latitude.

For each observing time, 0000 UT for instance, and at each grid point a single one year time series has been made consisting of daily values, each of which is a 17 year average for the date. This may be considered the raw 0000 UT climatology. Next the smooth 0000 UT climatology is obtained by retaining the mean plus four harmonics (with periods 1 year, 1/2 year, 1/3 year and 1/4 year). Four harmonics is arbitrary, but a reasonable choice in view of *Epstein* [1988]. Note that the 0000 and 0600 UT climatologies are made independently from each other, i.e., the harmonic smoothing is performed on once-a-day data involving the whole calendar year, but there is no explicit smoothing on subdaily time scales.

The data used in this study are the (smooth) climatologies at 0000, 0600, 1200 and 1800 UT. We use the climatology at the 15th of the month and denote this as, for example, the January climatology.

3. A Preliminary Look at the Tides

Figure 1 shows in four panels the difference of the 0000, 0600, 1200 and 1800 UT surface pressure climatologies from the daily mean January climatology. The latter is calculated as the straight average of the four. One can see very large scale anomalies of alternating sign with an amplitude of over 2 mbar. The center of the anomalies is somewhat close to the Equator, but the phenomenon is clearly global in scale and has a large meridional extent. Zonal wavenumber 2 dominates the total field, and at each of the four observing times there are two maxima and minima. The shape of the pressure anomalies is somewhat ragged and appears to take on the details of the continent-ocean outline in some places at certain times, thus pulling away the maximum values from the Equator. Although the semidiurnal cycle

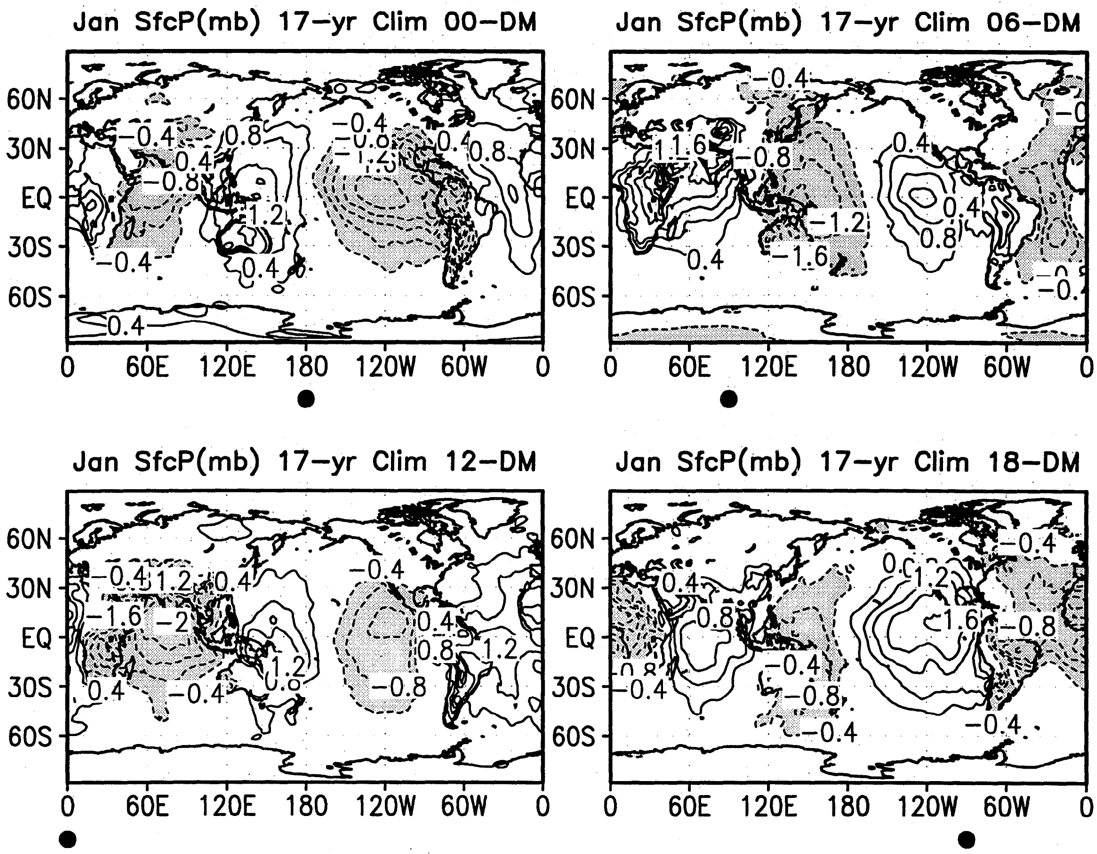

Figure 1. January 1979-1995 averaged surface pressure anomaly at 0000, 0600, 1200 and 1800 UT in January. Anomaly is defined as departure of climatology at a given time from the daily mean. Contours are drawn for every 0.4 mbar, no zero line. Negative values are shaded. Solid dot along the longitudinal axis indicates position of the Sun at local noon.

is known to be dominant, we note that maps separated by 12 hours are by no means identical, nor are the maps separated by 6 hours the opposite of each other.

The crux of the paper is that from Figure 1 alone, it would be impossible to tell whether the tides are traveling waves or standing oscillations. If the tides travel, one cannot tell from Figure 1 whether they go east or west. This is caused by the teasing combination of the dominance of the semidiurnal cycle and the 6 hourly sampling. For instance, at 170°W the tides appear to have nearzero amplitude at the four reporting times and a linear (or higher order) time interpolation will keep the amplitude zero at all times. Where the amplitude is large, at 120°W for example, LTI will be closer to the truth but still subject to improvement if only the anomaly motion could be used in the interpolation scheme. It is also clear that an estimate of the time derivative would be impossible to obtain from 6 hourly data. The proposed interpolation is intended to overcome these problems.

Figure 1 is treated as a display of the full tides at four times, not just the semidiurnal tide at these times (which, admittedly dominates at all times). No doubt there are errors in these fields but we assume, in effect, that these four panels are the best depictions available. The interpolation method described below keeps all empirical details because we do not want to a priori assume, for instance, that the tides are the same at all longitudes. Nor should they, because the forcing varies with longitude, particularly relating to land, ocean, and topography.

4. The Empirically Derived Motion of Spatial Harmonic Waves

The data shown in Figure 1 have been decomposed into Fourier components along all circles of constant latitude. Table 1 shows information about the amplitude and phase of zonal harmonic waves along 0.95°N (the Gaussian gridpoint in the northern hemisphere nearest to the equator) in January. From the amplitudes one can see the general dominance of wave $m = 2$, although $m = 1$ has 30-50% of the amplitude of $m = 2$. Waves 3-10 are smaller but not negligible and, moreover, do not show a monotonic decrease with m. There is significant variation of amplitude of some waves with time of day. For example $m = 4$ is largest at 0600 and 1800 UT, while $m = 1$ is largest at 1800 and 0000 UT. This is significant in the sense that it can be observed in all months. (See Table 2 which is as Table 1, but for

Table 1. Amplitude(x 0.1 mbar) of Surface Pressure Anomaly along 0.95°N (as Displayed in Figure1) for Zonal Harmonic waves $m = 0 - 10$, Four Times a Day, the Phase Difference of these Harmonics in the 6 Hr Time Increments, and Phase Differences Adjusted on the Assumption of Theoretical Tides for $m = 1 - 5$

	Amplitude				Phase Difference				
m	0000 UT	0600 UT	1200 UT	1800 UT	0000-0600 UT	0600-1200 UT	1200-1800 UT	1800-0000 UT	$p0$
0	-3.8	3.2	-0.2	0.9	0.0	0.0	0.0	0.0	
1	8.2	5.3	5.5	7.5	-90.2	-73.1	-83.8	-112.8	
2	14.5	14.9	15.1	14.6	165.0	179.7	-165.2	-179.5	
3	3.6	1.3	2.1	3.6	132.3	-23.0	126.7	124.1	
4	0.9	2.0	0.6	2.6	-49.8	-88.7	-89.4	-132.1	
5	2.4	2.3	2.5	2.1	-93.3	-91.3	-92.6	-82.9	
6	2.0	0.6	2.3	0.7	137.3	61.6	-168.4	-30.5	
7	1.1	1.5	1.2	1.2	103.9	92.1	94.5	69.4	
8	0.4	0.9	0.8	0.4	70.0	153.2	21.3	115.5	
9	0.8	1.0	0.5	0.6	129.0	81.7	83.1	66.2	
10	0.3	0.0	0.8	0.5	130.5	41.5	171.7	16.3	
					After Phase Adjustment				
1					-90.2	-73.1	-83.8	-112.8	-90
2					-195.0	-180.3	-165.2	-179.5	-180
3					-227.7	-383.0	-233.3	-235.9	-270
4					-409.8	-448.7	-449.4	-492.1	-360
5					-453.3	-451.3	-452.6	-442.9	-450

The phase difference $p0$ is the theoretical value for tides moving precisely with the Sun.

April, July and October.) The zonal mean is the only harmonic amplitude with the sign retained. Near the equator the zonal mean pressure (-0.38) is 0.38 mbar below the daily mean at 0000, increasing to +0.32 at 0600 UT etc., showing a semidiurnal variation as well. At higher latitudes the daily variation in zonal mean dominates over any wave component.

The phases of the waves shown in Figure 1 are presented in Table 1 in terms of the phase difference between the 0000 and 0600 UT positions, 0600 and 1200 UT and so on. Wave $m = 1$ is confidently analyzed to have moved westward at an average speed of close to 90° per 6 hours, but with significant variation during the day. During the 0600-1200 UT period the speed is smaller, and during 1800-0000 UT the phase speed is higher. Again, we dare to present these variations as empirical facts because it happens in all months (see Table 2). Wave 2 moves close to 180° every 6 hours, but from Table 1 alone we cannot be sure whether the motion is to the east or to the west.

For $m = 2$ and higher waves, the phase shifts are ambiguous because they are close to or larger than half a wavelength per sampling time. Some forceful intervention is needed to resolve the ambiguity. In general, the phase of a periodic wave is arbitrary by 360, and we do not violate the empirical 6 hourly shifts by adding multiples of +/− 360 to the numbers in Table 1. Among the infinite possibilities thus obtained, we chose the one that makes for a zonal wave motion closest to a westward motion of one quarter of the earth per 6 hours. In doing so, we force the results of the theory to hold to some degree but without discarding any empirical findings. The theory alluded to [*Chapman and Lindzen*, 1970; *Andrews et al.*, 1987] explains the tides as related to solar heating which forces the tides to move along with the Sun on a westward course.

In the lower part of Table 1, the postprocessed phase differences are given. Understandably, $m = 1$ needs no change at all, but $m = 2$ needs two positive numbers (suggesting eastward motion), turned to -195.0 and -180.3. For higher wavenumbers, the adjustment becomes larger and larger in terms of their own wavelength. The behavior of $m = 4$ is rather strange: it moves somewhat faster than the Sun at all times of the day.

Note that we did not impose the predetermined phase shift

$$p0 = 90° \text{ of longitude westward per 6 hours}$$

uniformly on all waves. Table 1 shows considerable departure from $p0$. Nevertheless, because of the dominance of $m = 2$ in amplitude, and the closeness of the speed of $m = 2$ to $p0$, the results could to first order be interpreted as moving all waves by $p0$. This is the method followed by *Madden* [1997]. One can easily tell, however, that applying $p0$ to all waves is not correct. Applying $p0$ to all waves is the same as translating the

Table 2. The Same as Table 1, but for Different Months

Time m	Amplitude 0000 UT	0600 UT	1200 UT	1800 UT	Phase Difference 0000-0600 UT	0600-1200 UT	1200-1800 UT	1800-0000 UT
					April			
0	-3.0	2.6	0.0	0.4	0.0	0.0	0.0	0.0
1	7.1	4.9	4.7	7.8	-93.4	-56.3	-99.4	-110.9
2	15.5	16.2	17.4	16.6	167.9	178.8	-168.8	-177.9
3	2.7	1.2	2.7	3.3	116.6	9.3	133.6	100.6
4	1.5	1.2	0.6	2.1	9.1	-158.6	-33.4	-177.1
5	2.1	2.1	3.0	2.0	-68.2	-111.4	-94.3	-86.1
6	0.9	0.1	2.6	1.7	-118.8	-52.4	-171.7	-17.0
7	0.5	1.5	1.3	1.1	100.6	115.6	104.4	39.4
8	0.5	0.5	0.6	0.4	50.4	162.8	-16.3	163.1
9	0.6	1.1	0.5	0.8	165.8	39.1	150.2	4.9
10	0.2	0.5	0.6	0.6	101.3	-126.7	-135.4	160.7
					July			
0	-2.4	2.5	-0.6	0.5	0.0	0.0	0.0	0.0
1	5.9	5.1	3.5	7.2	-96.5	-54.3	-100.5	-108.7
2	13.9	13.7	14.6	15.0	169.5	-176.5	-170.2	177.3
3	1.8	1.6	1.9	2.1	141.8	18.9	147.8	51.5
4	0.7	1.4	0.8	1.6	55.1	-138.6	-84.3	167.9
5	1.4	2.2	2.3	2.4	-70.8	-101.5	-102.3	-85.4
6	1.0	1.2	1.5	1.6	179.8	51.7	176.1	-47.6
7	0.3	1.5	0.8	1.5	113.4	88.7	113.4	44.5
8	0.6	0.6	0.6	0.7	64.0	103.6	78.1	114.3
9	0.3	0.7	0.2	0.7	154.5	13.7	161.8	30.0
10	0.3	0.5	0.6	1.2	23.3	-79.2	-140.1	-164.0
					October			
0	-2.4	3.1	-0.7	0.1	0.0	0.0	0.0	0.0
1	9.0	5.0	5.9	7.2	-90.1	-75.7	-77.4	-116.9
2	15.5	15.8	16.2	15.8	165.9	178.1	-166.3	-177.7
3	3.0	1.4	2.3	3.6	104.5	16.9	125.3	113.2
4	1.4	1.4	0.9	1.9	11.1	177.7	-4.9	175.9
5	2.4	2.2	3.2	2.4	-80.0	-96.0	-104.0	-80.0
6	0.8	0.8	2.4	2.5	-173.6	-2.0	-178.0	-6.4
7	1.1	1.5	1.7	2.0	28.7	118.8	91.8	120.7
8	0.8	0.5	0.8	0.5	82.4	99.2	73.7	104.6
9	0.5	1.1	0.2	0.6	-137.5	170.9	51.5	-84.9
10	0.5	0.7	0.4	1.1	67.2	-100.1	-127.0	159.9

whole map westward. From Figure 1 one can see that the 0000 UT panel, after a 1/4 Earth westward translation, does not yield the 0600 UT field. For instance the negative over the East Pacific has a round smooth appearance at 0000 UT, while 6 hours later the negative over New Guinea is more meridionally elongated and contracted in the longitudinal direction. Such changes are reflected in departures from $p0$ and in amplitude variations.

5. Wave Interpolation Procedure

The procedure for interpolation, following DQ, can be stated as follows. We have observed fields, $O(t)$ and $O(t+6)$, and we want an interpolated field at $t+x$, where $0 < x < 6$ hours. $O(t)$ and $O(t+6)$ are given in terms of zonal harmonics. $O(t)$ is integrated in time for x hours, by propagating each zonal harmonic in $O(t)$ forward in time for x hours, with the adjusted phase speed as shown in Table 1. This yields $F^+(t+x, O(t))$. Next $O(t+6)$ is moved backward in time for $6-x$ hours, by propagating each zonal harmonic backward in time for $6-x$ hours, i.e., by the opposite of the adjusted phase propagation shown in Table 1. This yields $F^-(t+x, O(t+6))$. We now have two fields valid at $t+x$, and we average them with weights proportional to the elapsed time as follows,

$$I(t+x) = [(6-x)F^+(t+x) + xF^-(t+x)]/6. \quad (1)$$

Note that we keep the phase speed constant during the 6 hour interval, but this constant changes four times

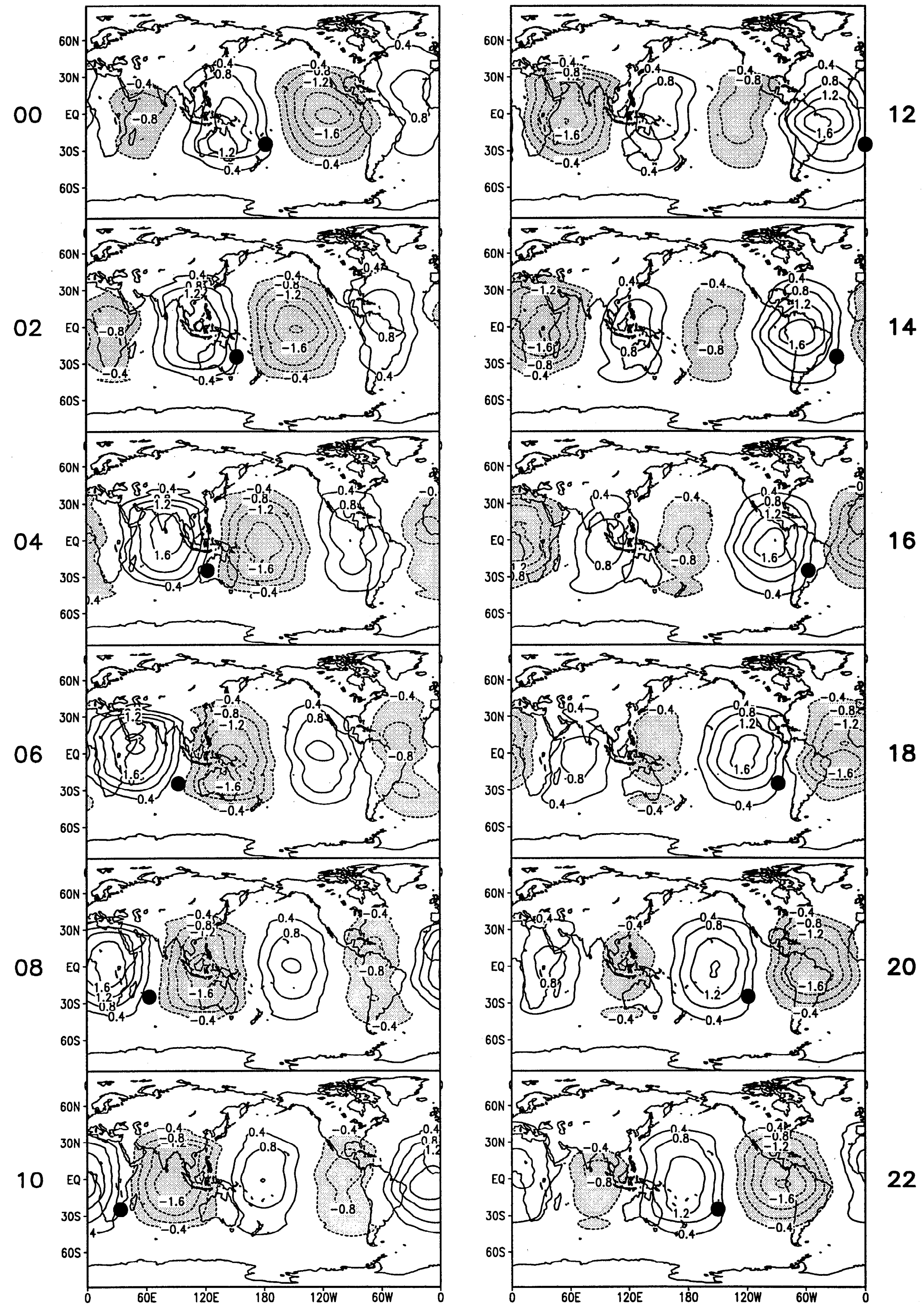

Figure 2. As Figure 1, but now every 2 hours after applying a wave interpolation scheme. The fields are truncated to zonal wave $m \geq 2$.

a day (see Table 1). Originally we had planned to calculate one single speed valid for any time of the day, using the phase shifting method more literally as in DQ. However, the variations of speed during the day, albeit only in four discrete steps, appear credible enough to be applied here. Because of this circumstance, $F^{+}(t+x)$ equals $F^{-}(t+x)$ harmonic by harmonic in terms of phase (not in terms of amplitude), so Eq. 1 could have been written simpler. In executing Eq. 1, the fields go exactly through the observed states $O(t)$ and vary smoothly in between. The wave amplitudes are, in the process, interpolated linearly in time.

6. Tides by the Hour

Figure 2 presents the surface pressure anomalies at a choice of in-between times. In order to save space, we only show the fields at 0000, 0200, 0400, ... 2200 UT. The 0000, 0600, 1200 and 1800 UT fields differ slightly from the corresponding panels in Figure 1 in that the number of zonal waves is truncated to 2, which makes for a smoother appearance. Each of the anomaly centers is seen to move and change its shape gradually. At all times we see one pair of side-by-side strong positive and negative values and another pair of much weaker side-by-side positive and negative values. The Sun (indicated with a small solid circle in Figure 2) is in between the strong pair. The anomalies appear to accelerate westward once they reach the open Pacific. Following each center, one can see that while the identity is largely maintained over the 24 hour path, the amplitude has a peculiar daily variation. The negative center at 120°W at 0000 UT has its extreme value (>2.4 mbar) at 0000 UT, then decreases to 1.6 mbar at 0600 UT, to recover slowly over the next 18 hours. The positive center at 140°E at 0000 UT has the smallest magnitude at 0000 UT (~1.2 mbar), goes through a semidiurnal amplitude variation, with largest values at 0600 and 1800 UT (~2 mbar). It follows that one can not design a Sun-synchronous observing system that eliminates the tidal variation altogether.

Figure 3 shows a time-longitude cross section along 0.95°N, based on 10 zonal waves and the zonal mean. In the figure the longitudes are entered every 22.5° and time every hour, with 0000 UT repeated at the bottom and Greenwich longitude repeated on the right. Again we see a perfectly reasonable propagation. The largest anomaly value is found at an off time, 0700 UT and 22.5°, reaching +2.4 mbar. The thick dashed line represents position of the Sun at local noon.

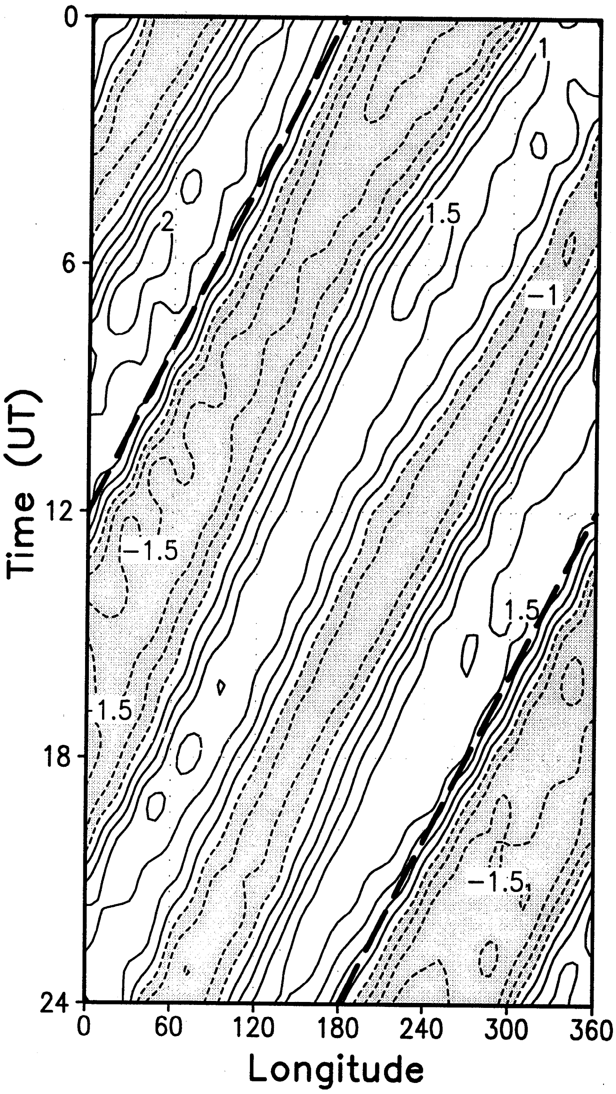

Figure 3. A Hovmoller diagram of the tides in Reanalysis for January along 0.95°N. Shown are climatological surface pressure anomalies as a function of longitude (data entered entered every 22.5°) and time of day (each hour). The data are truncated at zonal wavenumber 10. Negative values are shaded. Thick dashed line indicates location of the Sun at local noon.

7. Amplitude and Phase of Tides along the Equator

Using the data shown in Figure 3, we have made a Fourier analysis in time from 24 hourly values at each grid point along 0.95°N. Table 3 shows amplitude and phase of the $s = 1$ and $s = 2$ components thus obtained, as a function of longitude. Wave $s = 1$ has an amplitude of 0.4 to 0.9 mbar, the higher (lower) values being attained just west of Greenwich (120°E). On the other hand $s = 2$ has an amplitude of 1.3-1.7 mbar, the highest (lowest) values being observed near 135°W (22.5°W). The phase of $s = 1$ is close to 1800 local time, while $s = 2$ has its maximum at 1000 and 2200. The first two temporal harmonics descibe most of the local variance, the precise amount ranging from 99% near the dateline to 88% near and west of Greenwich.

Using the 24 hourly values, we find the pressure maximum to occur anywhere from 0900 to 1200 local time, while the minimum is reached between 1600 and 2000, depending on longitude. The range is over 4 mbar east of Greenwich and as low as 3.2 mbar at 135°E. Compared to the established texts [*Chapman*, 1951], the phase seems reasonably close to what is observed, but the amplitude in the Reanalysis is higher by about 10-40%.

In a long term 1979-1995 climate simulation of the Reanalysis model (no data assimilation, referred to as AMIP) we found the amplitudes of the tides to be about 10% less than in the Reanalysis. As an illustration, Figure 4 (upper right) is the same as Figure 3 (repeated in Figure 4 upper left), except for pure model data. In terms of phase, the model and analysis versions of the tide are quite close (more on this in the next section). Curiously enough, we can not blame the model

Table 3. Quantitative Information Regarding the Tides Along 0.95°N in January as a Function of Longitude in 22.5° Increment

	Longitude																
	0		45		90°E		135		180		135		90°W		45		0
Amp S1(x 0.1 mb)	9.	8.	7.	6.	5.	4.	4.	4.	5.	5.	6.	7.	8.	9.	9.	9.	9.
Amp S2(x 0.1 mb)	13.	14.	15.	16.	16.	15.	14.	14.	15.	17.	17.	17.	16.	14.	13.	13.	13.
Phase S1(UT)	6.	5.	3.	2.	24.	22.	20.	18.	17.	16.	14.	13.	12.	11.	9.	8.	6.
Phase S1(LT)	6.	6.	6.	6.	6.	5.	5.	5.	5.	5.	5.	6.	6.	6.	6.	6.	6.
Phase S2(UT)	10.	9.	7.	6.	4.	3.	1.	11.	10.	8.	7.	6.	4.	3.	1.	12.	10.
Phase S2(LT)	10.	10.	10.	10.	10.	10.	10.	10.	10.	10.	10.	10.	10.	10.	10.	10.	10.
Exp Var(%) (S1+S2)	89.	88.	90.	93.	96.	98.	98.	98.	99.	99.	98.	96.	92.	89.	88.	88.	89.
Time of Max(UT)	10	8	7	5	4	3	1	24	22	21	19	19	15	13	12	11	10
Time of Max(LT)	10	10	10	10	10	11	10	11	10	11	10	12	9	9	9	10	10
Time of Min(UT)	19	17	15	14	12	10	8	6	5	3	1	1	24	24	22	21	19
Time of Min(LT)	19	19	18	19	18	18	17	17	17	17	16	18	18	20	19	20	19
Max-Min(x 0.1 mb)	37.	41.	40.	39.	36.	34.	32.	35.	38.	39.	39.	40.	37.	37.	39.	39.	37.
							From 6 hourly data (no interpolation)										
Amp S1(x 0.1 mb)	10.	16.	9.	1.	5.	8.	3.	1.	5.	6.	5.	5.	10.	18.	6.	1.	10.
Amp S2(x 0.1 mb)	9.	2.	12.	16.	12.	3.	13.	12.	4.	8.	16.	17.	10.	0.	10.	12.	9.
Phase S1(UT)	8.	3.	6.	2.	23.	21.	20.	17.	16.	15.	13.	13.	14.	10.	8.	5.	8.
Phase S1(LT)	8.	5.	9.	6.	5.	4.	5.	3.	4.	5.	4.	6.	8.	6.	5.	4.	8.
Phase S2(UT)	3.	-3.	-3.	-3.	-3.	3.	3.	3.	3.	-3.	-3.	-3.	-3.	-3.	3.	3.	3.

The upper 4 entries are the amplitude of S1 and S2, their phase in hours both in UT and local time(LT), and the variance explained by the local 1200(S2) and 2400(S1) hour periods combined. The next three entries are the times of absolute maximum and minimum, and the range in terms of maximum-mininum. The last three entries are estimates of the amplitude of S1, S2 and phase of S1 based on raw 6 hourly data without wave interpolation.

that is used for the production of the guess field for the stronger tides in the analysis. The rather successful simulation of the tides in numerical weather prediction (NWP) models used in climate mode has been demonstrated by *Zwiers and Hamilton* [1986].

At the bottom of Table 3, we have amplitude and phase of $s = 1, 2$ derived from the 6-hourly data, i.e., what we would know without the DQ wave interpolation. Obviously, the phase for $s = 2$ can not be determined, but note that $s = 1$ is also poorly described, even in terms of amplitude: the diurnal and semidiurnal effects are quite mixed up.

8. Verification of the Interpolation Method

So far we have shown interpolated fields and a Hovmoller diagram, and commented that they look reasonable. However, a formal verification would naturally be more convincing. Are the interpolated fields close to what Reanalysis would be if the output were saved and provided hourly? Some comments are in order perhaps as to why Reanalysis gives output every 6 hours only, instead of hourly (in which case the DQ wave interpolation method would have no clear application). Apart from the obvious increase in data management, the utility of more frequent analyses is limited because there are no more observations to be assimilated. In fact, with most radiosondes at 0000 and 1200 UT, we are pushing it as it is, calling the 4 times daily fields *analyses* as in analyses of observations. Hourly output would be primarily model and just a little surface and satellite data, except at 0000 and 1200i UT when the all important radiosondes come in. (Analysis of the tides is not a high priority and has been considered a nuissance in weather forecasting circles [*Riehl* 1954].) As a consequence, interrupting the computer run programmed in 6-hourly blocks, for costly input/output breaks and restarts, is not normally done at operational weather forecast centers such as the National Centers for Environmental Prediction (NCEP), where time efficiency is essential.

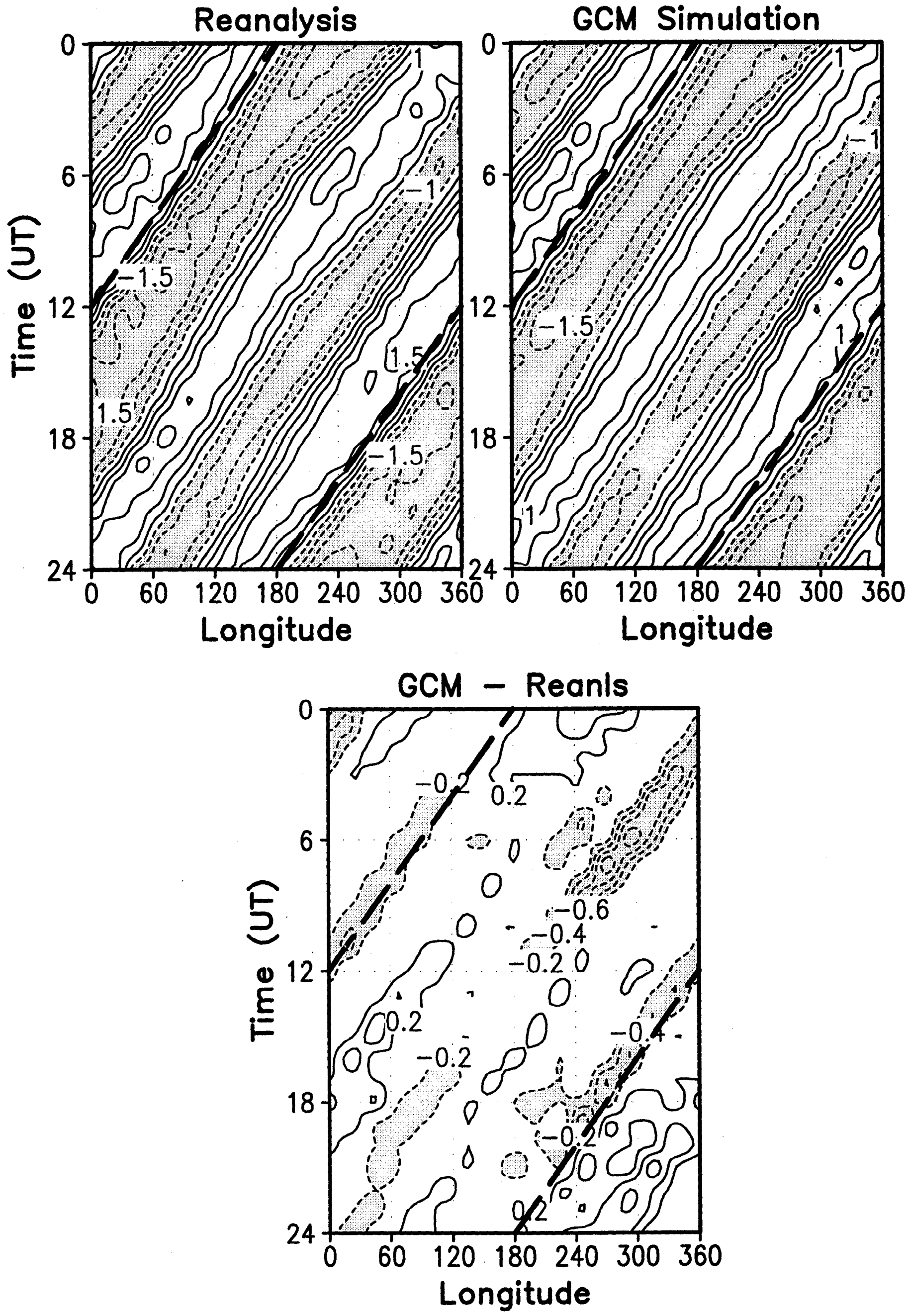

Figure 4. A Hovmoller diagram of the tides in a 17 year AMIP run (upper right) and Reanalysis (upper left) for January along 0.95°N. Shown are climatological surface pressure anomalies as a function of longitude (data entered every 22.5°) and time of day (each hour). The data are truncated at zonal wavenumber 10. The difference (with contours every 0.2 mbar) is shown at the bottom. Both AMIP and Reanalysis figures are based on 6 hourly data. Negative values are shaded. Thick dashed line indicates location of the Sun at local noon.

One possibility would be to verify against hourly station data, but this would be only at a few points, and we would be confusing the issue by verifying the data assimilation system and interpolation method together. A better way of verifying the method as such is to use pure model data. We have already shown in Figure 4 that the model (without any atmospheric observation data assimilated in a 17 year run) has quite realistic tides. Figure 4 was based on 6 hourly output which in combination with the DQ method yielded hourly values. We proceeded to make a special model integration of 2 months only, starting December 1, 1996, in which we saved gridded output every hour. Of course, 2 months may be somewhat noisy, although we verified that the first and second months were in fair agreement. In Figure 5 we compare a display of the tides along 0.95°N based on hourly data (top left), based on 6-hourly data with DQ interpolation method (top right), and the dif-

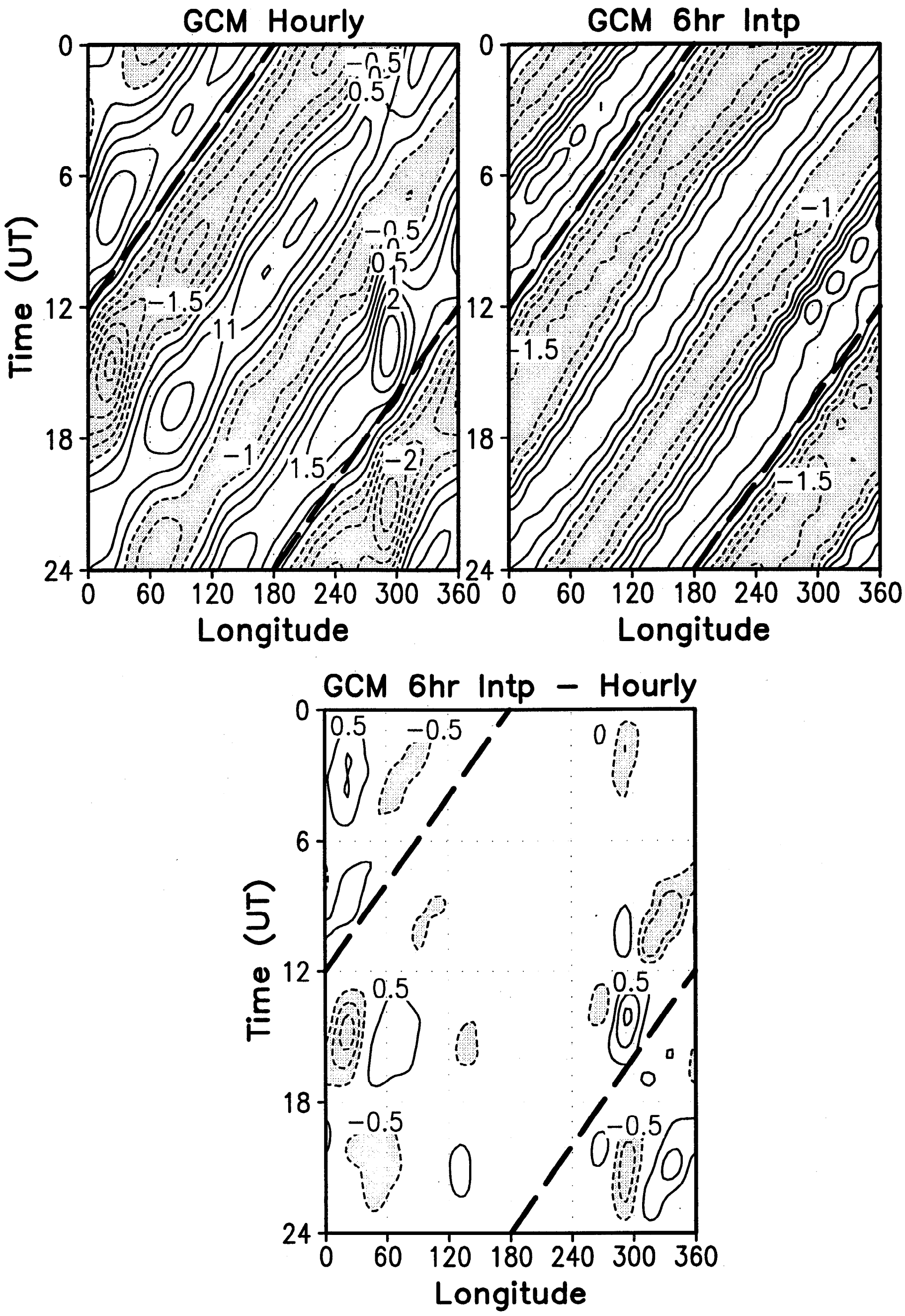

Figure 5. A Hovmoller diagram of the tides in a 2 month AMIP run for January along 0.95°N, based on hourly data (upper left) and 6 hourly interpolated data (upper right). Shown are climatological surface pressure anomalies as a function of longitude (data entered every 22.5°) and time of day (each hour). The data are truncated at zonal wavenumber 10. The difference (with contours every 0.5 mbar; no zero line) is shown at the bottom. Negative values are shaded. Thick dashed line indicates location of the Sun at local noon.

ference (bottom). The difference is generally only a few tenths of a millibar, thus verifying that the DQ method works quite well. Exceptions are over land areas where tides (as analyzed from hourly data) appear to halt, before continuing their westward track. The interpolation scheme assumes that all waves (out to $m = 10$) move at a constant speed (estimated from data 6 hours apart). Therefore, details of the physics of the diurnal variation can not be studied completely with interpolated data.

9. Conclusions and Discussion

We have designed a method, based on anomaly zonal waves moving at empirically determined speeds, that can be used to interpolate the tides in Reanalysis, available currently only at 0000, 0600, 1200, and 1800 UT, to any time in between. The interpolation scheme seems to generate reasonable results, and a verification on a limited set of hourly data from a 2 month model run was quite satisfactory. Simple interpolation schemes (linear and higher order local time interpolation) can not address this problem because of the poor sampling relative to the semidiurnal (and higher frequency) components. The trick is in *adjusting* the empirically found 6-hourly phase shift for $m \geq 2$, such that the phase speed is somewhat close to $-90°$ of longitude per 6 hours.

The proposed interpolation is a reasonable procedure only for solar heating related regular moving variations. If someone wanted to study the lunar tides (which measure only hundredths of a millibar [*Chapman and Lindzen* 1970]), the method as applied here would not be helpful, since the lunar day lasts about 50 minutes longer than a solar day, and the empirical speeds needed to be adjusted in a different way. Moreover, the storage of data at the (solar related) times of 0000, 0600, 1200 and 1800 UT makes the detection of lunar tides challenging, even if the magnitude was not so small. The model's guess field used in the analysis is made by a model unaware of the moon's gravitation, thus making it unlikely that the analysis contains proper lunar tides. In short, we do not recommend the Reanalysis gridded data for study of the lunar tides.

The tides as found in the Reanalysis are different numerically and even in concept from what was previously believed to be standard. For instance, *Haurwitz* [1965] presents a zonal wavenumber 1 in surface pressure of amplitude 0.59 mbar at the Equator, traveling westward in 24 hours. The amplitude is not only stronger in the Reanalysis (daily averaged 0.67 mbar, in January), but has itself a large daily variation (0.53 to 0.82 mbar). Moreover, the westward phase speed has a daily variation. In allowing daily variations in amplitude and phase speed for zonal waves, we have given up the convenient but simplistic view of a one-to-one relationship between $m = 1$ and $s = 1$, $m = 2$ and $s = 2$, etc.

Reanalysis appears to have stronger tides than what has been reported classically based on hourly surface station data. For $m = 1$ and 2, Reanalysis has (daily averaged) amplitudes of 0.67 and 1.47 mbar respectively, while the literature [*Haurwitz*, 1965; *Hsu and Hoskins*, 1989] quotes 0.59 and 1.16 mbar for these components. Tides in Reanalysis is decidely stronger by 10-40%, and probably too strong. Haurwitz used extensive hourly station data for many years and his estimates must be considered quite accurate, at least where data are plentiful.

Haurwitz also reported a (semi) diurnal oscillation in the zonal mean pressure; we found much the same (see the $m = 0$ component in Table 1 and 2, for instance), and again, Reanalysis seems (too?) strong. For this component the DQ method reduces to linear interpolation. The zonal mean oscillation is dwarfed by the travelling components at low latitudes, but the reverse is true at high latitudes. When averaging over the whole globe Reanalysis shows a (semi)diurnal oscillation with an amplitude of about 0.1 mbar. While this appears hard to explain at first sight (should not global mean mass be nearly constant?), this strange feature has been noted before by *Wilkes* [1949] and *Haurwitz* [1965]. Perhaps an explanation should be sought, either physical, artificial (data treatment), or related to the daily cycle in the number of reports and the data distribution (land versus ocean). The accepted explanation for the annual cycle in global mean pressure, i.e., the variable atmospheric water content [*Trenberth and Guillemot*, 1994; *Van den Dool and Saha*, 1993] is at least 1 order of magnitude too small to explain the daily cycle.

In an earlier paper [*Van den Dool and Saha*, 1993], we investigated the redistribution of atmospheric mass over the course of the annual cycle. The redistribution of mass during the day was not discussed then because the available data did not permit such an analysis. In particular, the time derivative of pressure cannot be evaluated from 6-hourly data. We believe we have solved this problem satisfactorily, although for some local details, nothing can substitute for hourly analyses of observations. We are now in a position to report (in a future paper) on the daily and annual redistribution of mass, both dry air (conserved globally) and precipitable water (subject to sources and sinks), both in a model and in Reanalysis.

The interpolation technique used here for the tides is basically the same as the one published by *Van den Dool and Qin* [1996] except that the wave speeds are completely different. While in DQ, *anomalies* were moving like slow Rossby modes, the tides are traveling at the much faster speed of roughly 90° of longitude westward per 6 hours. It could be difficult to separate fluid elements traveling at such vastly different speeds because the localtime scales are not well separated. In DQ a 1 day time separation (0000-0000 UT) was used to study the speed of climate anomalies travelling at Rossby like speeds. By using a 1 day step, the tides were circumvented rather than addressed. However, if one wants to use the richer Reanalysis data every 6 hours, the removal, or filtering of the tides becomes critically important. Taking out the climatology (as defined here) every 6 hours may still not be good enough because the tides undergo modulations in strength on timescales of the weather, and subtracting out the long term mean tides still leaves poorly sampled *anomalous tides* racing around at enormous speeds.

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